EVIDENCE FOR THE EVOLUTIONARY SEQUENCE OF BLAZARS: DIFFERENT TYPES OF ACCRETION FLOWS IN BL LAC OBJECTS

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ABSTRACT

The limits on the mass of the black hole in 23 BL Lac objects are obtained from their luminosities of the broad emission line Hβ on the assumption that broad emission lines are emitted from clouds ionized by the radiation of the accretion disk surrounding a black hole. The distribution of line luminosity $L_{H\beta}$ of all these BL Lac objects suggests a bimodal nature, although this cannot be statistically proven on the basis of the present, rather small sample. We found that standard thin disks are probably in the sources with $L_{H\beta} > 10^{41}$ erg s^{-1}. The central black holes in these sources have masses of $10^{8-10} M_\odot$, if the matter is accreting at the rate of $0.025 \dot{M}_{\rm Edd}$. For the sources with $L_{H\beta} < 10^{41}$ erg s^{-1}, the accretion flows have transited from standard thin disk type to the ADAF type. The lower limits on the mass of the black hole in these sources are in the range of $1.66 - 24.5 \times 10^8 M_\odot$. The results support the evolutionary sequence of blazars: FSRQ$\rightarrow$LBL$\rightarrow$HBL.

Subject headings: BL Lacertae objects: general—galaxies: active—accretion, accretion disks

1. INTRODUCTION

The masses of the central black holes in quasars are crucial in understanding the evolution of quasars. Some different approaches are proposed to estimate the masses of the black holes in active galactic nuclei (AGNs), such as the gas kinematics near a hole (see Ho & Kormendy (2000) for a review and references therein). The black hole mass derived from the direct measurements on the gases moving near the hole is reliable, but it is only available for very few AGNs. For most AGNs, the central black hole masses can be inferred from the velocities of the clouds in broad line regions (BLRs) and the sizes of BLRs (Dibai 1981; Wandel, Peterson, & Malkan 1999; Kaspi et al. 2000). Most BL Lac objects have featureless optical and ultraviolet continuum spectra, and only a small fraction of BL Lac objects show very weak broad emission lines (Veron-Cetty & Veron 2000). It is therefore difficult to estimate their central black hole mass from the kinematics of their BLRs. The discovery of a tight correlation between stellar velocity dispersion and black hole mass in nearby galaxy bulges offers a new tool for estimate of the black hole mass (Ferrarese & Merritt 2000; Gebhardt et al. 2000). The black hole mass can be estimated from the measurement of bulge velocity dispersion using the $M - \sigma$ relation. The masses of the black holes in some nearby BL Lac objects have been estimated from the measurement of their bulge velocity dispersion (Falomo, Kotilainen, & Treves 2001, 2002; Barth, Ho, & Sargent 2002). Wu, Liu, & Zhang (2002) adopted the fundamental plane for ellipticals to estimate the velocity dispersion and then the hole masses for some AGNs. Fan, Xie, & Bacon (1999) derived the masses of the black holes in Mkn 501 and some other blazars from the gamma-ray variability time scale. They found that the masses are around $10^7 M_\odot$.

Ghisellini et al. (1998) used a large sample of blazar broadband spectra to study the blazar sequence. They suggested a sequence: HBL$\rightarrow$LBL$\rightarrow$FSRQ. This sequence represents an increasing energy density of the external radiation field that leads to an increasing amount of Compton cooling. The decrease of the maximum energy in the electron distribution causes the synchrotron and Compton peaks to shift to lower frequencies. Georganopoulos, Kirk, & Mastichiadis (2001) argued that the radiating jet plasma is outside the broad line scattering region in weak sources and within it in powerful sources, and the model fits to the spectra of several blazars proposed a sequence: FSRQ$\rightarrow$LBL$\rightarrow$HBL. The evolutionary sequence: FSRQ$\rightarrow$LBL$\rightarrow$HBL, has recently been suggested by D'Elia & Cavaliere (2000) and Cavaliere & D'Elia (2001). In this evolutionary sequence, less gas is left to fuel the central engine for BL Lac objects, and the advection dominated accretion flows (ADAFs) may be in most BL Lac objects. The blazar spectral calculations support this scenario (Böttcher & Dermer 2002).

There are several tens of BL Lac objects in which one (or more) broad emission line has been detected. It is therefore possible to infer the central ionizing luminosity through their broad line emission for these BL Lac objects. The limits on the central black hole mass can be obtained, if the accretion type in the central engine is known. The cosmological parameters $H_0 = 75$ kms^{-1} Mpc^{-1} and $q_0 = 0.5$ have been adopted in this work.

2. ESTIMATE ON THE IONIZING LUMINOSITY

It is not possible to measure the ionizing luminosity directly from observations on BL Lac objects, since the observed continuum emission from the jets is strongly beamed to us. In this case, the optical emission line luminosity can be used to estimate the central ionizing luminosity (Rawlings & Saunders 1991; Celotti, Padovani, & Ghisellini 1997; Cao & Jiang 1999).

We can estimate the ionizing continuum luminosity $L_{\lambda,\rm ion}$ at the given wavelength λ_0 as

$$L_{\lambda,\rm ion}(\lambda_0) = \frac{L_{\rm line}}{EW_{\rm ion}}, \qquad (1)$$

where λ_0 is the wavelength of the line, $EW_{\rm ion}$ is the equivalent width of the broad emission line corresponding to the ionizing continuum emission (different from the observed continuum emission).

The uncertainty in Eq. (1) is the value of $EW_{\rm ion}$, which may be different for individual sources. We estimate the value of $EW_{\rm ion}$ from the Boroson & Green (1992) sample. This sample

contains all 87 PG quasars ($z < 0.5$) with high quality optical spectra. The average value of $EW_{H\beta}$ is 100 Å for 70 radio-quiet quasars. Unlike blazars, the optical continuum of radio-quiet quasar has not been contaminated by the beamed synchrotron emission from the jet. We will take $EW_{ion} = 100$ Å and use the broad emission line Hβ to estimate the ionizing continuum luminosity of BL Lac objects. The BL Lac objects seem to follow the statistical behavior of quasars in the correlations between radio and broad line emission (Celotti, Padovani, & Ghisellini 1997; Cao & Jiang 1999). It may imply that the properties of BLRs in BL Lac objects are not significantly different from that in quasars. If the EW_{ion} of BL Lac objects deviates from that of quasars systematically, then the estimated black hole mass could be modified with EW_{ion} (see further discussion in Sect. 5).

3. ESTIMATE OF THE BLACK HOLE MASS

For a standard thin disk, the ionizing continuum luminosity is mainly determined by the central black hole mass and accretion rate. For a low accretion rate, the accretion flow will transit from standard thin disk type to the ADAF type (Narayan & Yi 1995; Yi 1996).

3.1. *Standard thin accretion disks*

The standard thin accretion disks are thought to be in most quasars (Koratkar & Blaes 1999). In this case, the luminosity at optical wavelength can be related with the disk luminosity by $L_d \simeq 9\lambda L_{\lambda,ion}(5100$ Å$)$ (Kaspi et al. 2000). The central black hole mass M_{bh} is then estimated by $M_{bh} \simeq 10^{-38}(L_d/\dot{m})M_\odot$, where $\dot{m} = \dot{M}/\dot{M}_{Edd}$. The ionizing luminosity $L_{\lambda,ion}$ can be inferred from $L_{H\beta}$, and we can finally estimate the black hole mass from the broad line luminosity $L_{H\beta}$, if $\dot{m}$ is known. For $\dot{m} = 1$, the lower limit of the black hole mass is available.

3.2. *ADAFs*

The transition of the accretion flow from the thin disk type to the ADAF type occurs while $\dot{m}$ decreases to a value below $\dot{m}_{crit}$ (Narayan & Yi 1995; Yi 1996). One possible mechanism for the transition might be the evaporation of the disk (Meyer & Meyer-Hofmeister 1994; Liu et al. 1999; Rózańska & Czerny 2000; Meyer-Hofmeister & Meyer 2001). Gu & Lu (2000) suggested that the transition can be triggered by the thermal instability of a radiation pressure-dominated standard accretion disk.

The spectrum of an ADAF: $L_\lambda(M_{bh}, \dot{m}, \alpha, \beta)$ can be calculated if the parameters M_{bh}, $\dot{m}$, α, and the fraction of the magnetic pressure β are specified. The parameter β is defined as $p_m = (1 - \beta)p_{tot}$. We can calculate the spectra of ADAFs using the approach proposed by Mahadevan (1997). For the fixed black hole mass M_{bh}, the optical luminosity L_λ increases with α. For AGNs, the viscosity α could be as high as 1, as suggested by Narayan (1996). In this work, We set $\alpha = 0.3$ to calculate optical luminosity L_λ (Yi 1996; Choi, Yang, & Yi 2001). The fraction of magnetic pressure $\beta = 0.5$ for equipartition cases. In fact, our numerical results show that the maximal optical luminosity L_λ^{max} always requires $\beta = 0.5$, if all other parameters are fixed. The accretion rate $\dot{m} < \dot{m}_{crit} \simeq 0.28\alpha^2$ should be satisfied for an ADAF (Mahadevan 1997). So, varying the accretion rate $\dot{m}$, we can find the maximal optical luminosity at λ_0 numerically for $\alpha = 0.3$ and $\beta = 0.5$ (see Fig. 1). We plot the maximal value of $\lambda L_\lambda^{max}(\lambda_0)$ varying with black

hole mass M_{bh} in Fig. 2. We can obtain a lower limit on the mass of the black hole from $L_{H\beta}$ using the relation $\lambda L_\lambda^{max} - M_{bh}$ plotted in Fig. 2.

For BL Lac objects, most accretion power may be carried by strong jets and the accretion flows may probably be described by the adiabatic inflow-outflow solutions (ADIOSs) (Blandford, & Begelman 1999). In this case, the flow is fainter than the pure ADAF considered here. The maximal $\lambda L_\lambda^{max}(\lambda_0)$ is therefore still valid for an ADIOS. It will not affect our estimate of the black hole mass limits.

4. MASSES OF BLACK HOLES IN BL LAC OBJECTS

Donato et al. (2001) complied a sample of blazars observed in the X-ray band, which includes almost all HBLs, IBLs, and many LBLs. We collect all BL Lac objects in their sample and 1 Jy+S4+S5 catalogues (Stickel, Meisenheimer, & Kühr 1994; Stickel, & Kühr 1994, 1996) as our start sample. This sample includes most identified LBLs and HBLs. We search the literature for all sources with broad emission line fluxes, and this leads to a sample of 23 sources (listed in Table 1). Most of them are LBLs, except three HBLs: 0651+428, Mkn 421, and Mkn 501. The sources with relatively strong broad emission lines ($EW > 10$ Å) are considered as genuine HPQs by Veron-Cetty & Veron (2000) and are therefore not included in our sample. The source 3C 279 (1253−055) is classified as a BL Lac object in Veron-Cetty & Veron (2000) due to its small broad line equivalent width, though this source is usually regarded as a quasar in other literature.

Many sources in this sample have detected Mg II or Hα line emission instead of Hβ. We use line ratios reported by Francis et al. (1991) to estimate Hβ line luminosity $L_{H\beta}$ from the line luminosity of Hα or Mg II. The broad emission line luminosity $L_{H\beta}$ are listed in Table 1. The distribution of the line luminosity $L_{H\beta}$ is plotted in Fig. 3.

We use Eq. (1) and the line luminosity $L_{H\beta}$ to estimate the ionizing continuum luminosity at 4861 Å. The central black hole masses $M_{bh,1}$ and $M_{bh,2}$ can be estimated in the cases of a thin disk and an ADAF, respectively. The mass derived for the standard thin disk case also depends on accretion rate $\dot{m}$. The lower limit of $M_{bh,1}$ can be available by setting $\dot{m} = 1$. If the transition of the accretion flow from the thin disk type to the ADAF type occurs at $\dot{m} \sim \dot{m}_{crit}$, we can have an upper limit on $M_{bh,1}$ setting $\dot{m} = 0.025$ for $\alpha = 0.3$. For ADAFs, $M_{bh,2}$ is the lower limit, since the maximal optical continuum luminosity is calculated for the given black hole mass. We list the derived black hole masses in Columns (6) and (7) of Table 1.
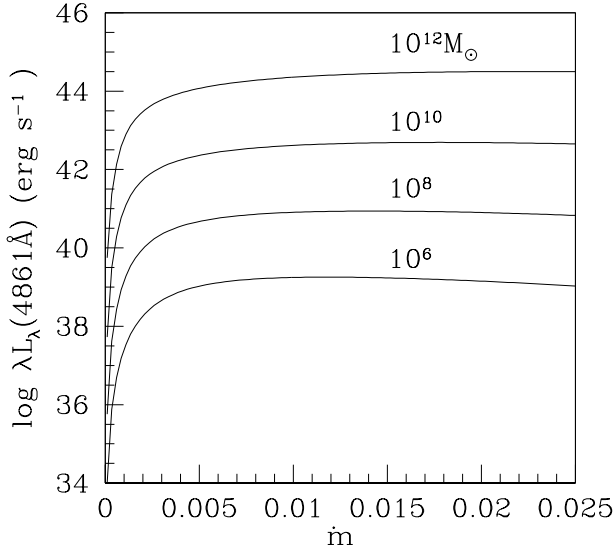
FIG. 1.— The optical luminosity of ADAFs at 4861 Å varies with accretion rate $\dot{m}$ for different black hole masses ($\alpha = 0.3$ and $\beta = 0.5$ are adopted).
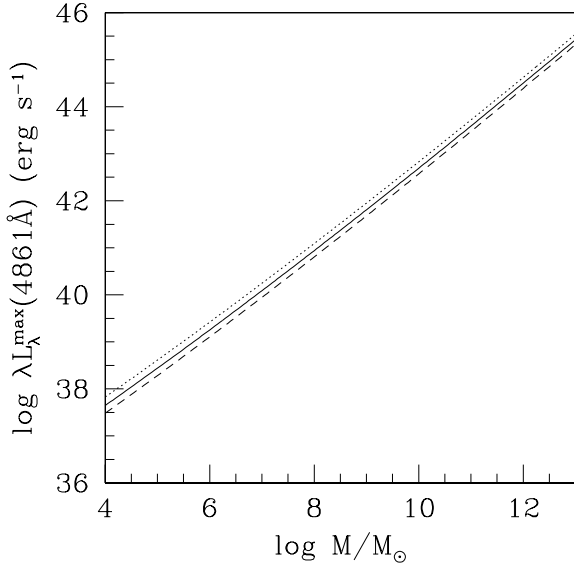

FIG. 2.— The maximal optical luminosity of ADAFs at 4861 Å as functions of black hole mass for different values α: $\alpha = 0.1$ (dashed line), 0.3 (solid), and 1 (dotted).
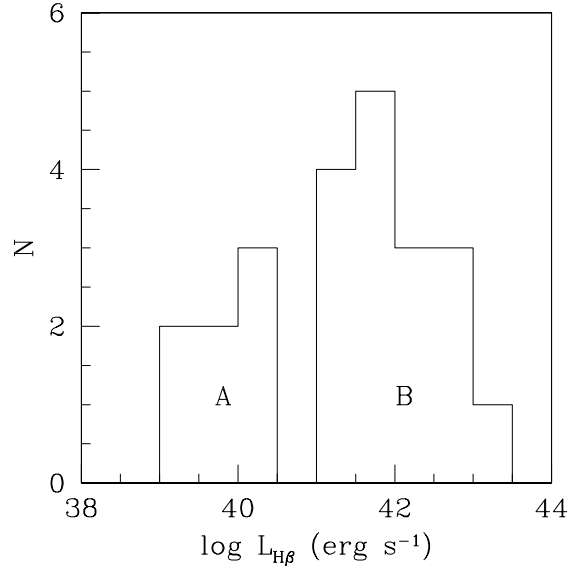

FIG. 3.— The distribution of the broad emission line luminosity $L_{H\beta}$.

5. DISCUSSION

The distribution of line luminosity $L_{H\beta}$ of all these BL Lac objects suggests a bimodal nature, although this cannot be statistically proven on the basis of the present, rather small sample (see Fig. 3). We define the sources with $L_{H\beta} < 10^{41}$ ergs s^{-1} as population A, and all others are in population B. It is still not clear whether this bimodal nature of line luminosities would hold for a larger sample. It would be interesting to perform high-sensitivity optical observations on a large sample of BL Lac objects.

For thin disk cases, the lower limits on the hole mass would be in 10^{4-8} $M_\odot$, while the upper limits on the hole mass would be in 10^{6-10} $M_\odot$ if $\dot{m} \sim 0.025$. For accretion rate $\dot{m} < 0.025$, the accretion flow would be in ADAF state. In this case, the lower limits on the black hole mass are in: 10^{8-12} $M_\odot$, which is similar to the results of Wang, Xue, & Wang (2001). Noting that this is the lower limit, the black hole mass could be much higher if the accretion rate is low or/and the viscosity α is small.

The masses of black holes in all sources of population B are in 10^{6-8} $M_\odot$ if $\dot{m} \sim 1$. It would be interesting to pay much attention on the seven sources in population A. If the accretion flows in these sources are in thin disk state, their central black holes would have masses 10^{4-6} $M_\odot$ for any value of $\dot{m}$. If the accretion rate $\dot{m}$ is lower than the critical value $\dot{m}_{\rm crit}$, the accretion flows in these sources are in the ADAF state. The lower limits on the mass of the black hole in these sources are in the range of $1.66-24.5 \times 10^8$ $M_\odot$. Falomo, Kotilainen, & Treves (2001) found that the mass of the black hole in Mkn 501 is 3.2×10^8 $M_\odot$ from the measurement of bulge velocity dispersion, while Barth, Ho, & Sargent (2002) derived the mass of $(0.9-3.4) \times 10^9$ $M_\odot$. Considering that our estimate (1.66×10^8 $M_\odot$) is the lower limit, the central black hole mass can be higher than the limit if the accretion rate is sufficiently low or/and the viscosity α is small. Our result is consistent with their results of Mkn 501 derived from bulge velocity dispersion. It may probably that the sources in population A have already been in ADAF state.

The sources in population B may have standard thin accretion disks surrounding the black holes, otherwise some black holes should be at least as huge as $10^{12} M_\odot$. If the accretion rate $\dot{m}$ of these sources is as small as ~ 0.025, slightly higher than the critical value below which the accretion flow would be in ADAF state, the black hole mass would be in $10^{8-10}\ M_\odot$. As the fact that most FSRQs have black hole mass higher than $10^8\ M_\odot$ (Laor 2000; McLure & Dunlop 2001; Gu, Cao, & Jiang 2001), this is compatible with the unified models of radio-loud quasars (Urry & Padovani 1995).

There are three HBLs in our sample in population A, and all sources in population B are LBLs. It may imply that the accretion flows in all HBLs are in ADAF state. The fact that no broad emission line has been detected for most BL Lac objects may imply that only a small fraction of LBLs have optically thick standard thin accretion disks surrounding the black holes with very low accretion rate close to $\dot{m}_{crit}$. We speculate that these LBLs will finally exhaust the gas near the hole and the disks will transit to ADAFs. Most other LBLs and HBLs without any broad emission line detected may be in population A, and the accretion flows have already been in ADAF state. Otherwise the black holes in these sources should be very small, if the accretion flows are in standard thin disk state. It is most probably that the BL Lac objects studied here with one (or more) broad emission line detected are in the intermediate state of the evolutionary sequence from FSRQ to BL Lac object. The fact that no HBL is in population B may imply that the evolutionary sequence of BL Lac objects should be LBL→HBL. The results present in this *Letter* support the evolutionary sequence FSRQ→LBL→HBL suggested by D'Elia & Cavaliere (2000). If this is the case, then the ratio of the BL Lac objects in population B to the remainder offers a clue to study the detailed evolutionary history of blazars, and it can also be a useful test on ADAF models.

If the evolution of blazars is really regulated by the gas near the black hole, the reprocessing optical depth of the BLR would decrease with the depletion of the gas near the hole, and the line EW_{ion} of the blazar would also decrease along the evolutionary sequence. The lower limits on the mass of the hole in evolving blazars should be modified with varying EW_{ion}. In this work, we used a single EW_{ion} to derive the masses of holes in blazars and found that the holes have similar masses for these two populations of BL Lac objects. In this case, the lower limits on the mass of the hole in the blazars evolving at a later stage would become systematically higher than that derived in this work. The derived hole masses seem to be consistent with the evolutionary sequence FSRQ→LBL→HBL.

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TABLE 1
BROAD EMISSION LINE DATA AND BLACK HOLE MASSES

Source	Redshift	Line	$\log L_{H\beta}$	References	$\log M_{bh,1}$[a]	$\log M_{bh,2}$[b]
0235+164	0.940	Mg II	42.2	CJ99	8.30	11.30
0537−441	0.896	Mg II	43.4	CJ99	9.58	12.60
0651+428[c]	0.126	Hα	40.5	M96	6.59	9.39
0814+425	0.258	Mg II	40.3	CJ99	6.38	9.15
0820+225	0.951	Mg II	41.4	CJ99	7.51	10.43
0823+033	0.506	Mg II	41.8	CJ99	7.90	10.86
0851+202	0.306	Hβ	41.3	CJ99	7.44	10.35
0954+658	0.367	Hα	41.0	CJ99	7.16	10.03
1101+384[c]	0.031	Hα	39.9	C00	6.05	8.78
1144−379	1.048	Mg II	42.7	CJ99	8.80	11.85
1253−055	0.536	Hβ	42.9	CJ99	9.07	12.14
1400+162	0.244	Hβ	40.5	SJ85	6.59	9.39
1538+149	0.605	Mg II	41.5	CJ99	7.60	10.52
1652+398[c]	0.0337	Hα	39.4	C00	5.57	8.22
1722+401	1.049	Mg II	41.5	VV00	7.63	10.55
1749+096	0.320	Mg II	42.2	VV00	8.28	11.28
1803+784	0.684	Hβ	42.9	CJ99	9.99	12.06
1807+698	0.051	Hβ	39.9	SJ85	6.03	8.74
1823+568	0.664	Hβ	41.7	CJ99	7.80	10.74
1921−293	0.352	Hβ	41.9	JB91	8.04	11.01
2029+121	1.215	Mg II	42.2	CJ99	8.29	11.29
2200+420	0.068	Hα	39.5	SJ85	5.63	8.28
2240−260	0.774	Mg II	41.8	CJ99	7.98	10.94

[a] in unit of $0.025 M_\odot / \dot{m}$

[b] in unit of $M_\odot$

[c] HBL

References. — C00: Cao (2000); CJ99: Cao & Jiang (1999); JB91: Jackson & Browne (1991); M96: Marcha et al. (1996); SJ85: Sitko & Junkkarinen (1985); VV00: Veron-Cetty & Veron (2000).